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The Effects of Prototype Helicopter Seat Cushion Concepts on Human Body Vibration Response

Suzanne D. Smith

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Human Effectiveness Directorate
Crew System Interface Division
2610 Seventh Street
Wright-Patterson AFB OH 45433-7901

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The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Instruction 40-402.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER



MARIS M. VIKMANIS
Chief, Crew System Interface Division
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THE EFFECTS OF PROTOTYPE HELICOPTER SEAT CUSHION CONCEPTS ON HUMAN BODY VIBRATION RESPONSE

Suzanne D. Smith

Armstrong Laboratory, Wright-Patterson Air Force Base, Ohio,
USA 45433-7901

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ABSTRACT

The driving-point impedance and transmissibility techniques were used to evaluate the effects of military helicopter seat cushions on human body vibration response. Small females (5th percentile or less for body weight) and large males (95th percentile or greater) were exposed to vibration in the frequency range of 3 to 21 Hz at 0.59 m/s² rms. Transmissibilities were calculated between the acceleration measured at selected anatomical sites, including the chest, head, spine (C₇), and thigh, and the input at the seat. Seating configurations included the rigid seat, a current inventory seat cushion, and a prototype cushion with an inflatable thigh support in both the deflated and inflated positions. Rigid mass tests showed that the single resonance frequency and associated magnitude peaks were significantly lower for the two prototypes. The most dramatic effects in the humans were observed in the magnitudes of the peak head and spine transmissibilities located between 4 and 6 Hz with the use of the prototype cushions. Both the deflated and inflated cushions significantly increased the peak head and spine transmissibilities in the females, while decreasing or attenuating the transmissibilities in the males as compared to the rigid seat and the current inventory cushion.

1. INTRODUCTION

Fatigue, discomfort, and back pain are common symptoms reported by operators of military air and ground vehicles. Bowden (1987) summarized the incidence of back pain among helicopter pilots, reporting that the onset of symptoms occurred in 2 to 4 hours with pain specifically being focused in the lumbar spine and buttocks. VanIngen-Dunn and Richards (1991) also found substantial reports of low back pain and general discomfort after about four hours of flight in both Army and Air Force Black Hawk helicopter pilots. The majority of the pilots attributed the discomfort to the seat configuration. The comments of the pilots suggested that the bottom cushions were too thin, concentrating loads on the ischial tuberosities, and that there was insufficient thigh support. Low back pain among helicopter pilots is considered to be the result of three factors: posture, workload, and vibration (Greth, 1994; VanIngen-Dunn and Richards, 1992). Helicopter seat cushion design concepts are being developed based on these factors with emphasis on improving posture, seated pressure distribution, compatibility with the cockpit environment, and safety. Posture and workload have been considered the most important factors since the effects of vibration in contributing to back pain have not been clearly delineated. However, helicopters can produce significant levels of vibration which include frequencies known to coincide with human body

resonances. A study on the Black Hawk helicopter by Pope et al. (1985) did show that the vehicle vibration environment produced significant discomfort in the lower back and in the buttocks. The general recommendation has been to use cushion materials which minimize the transmission of vibration to the human, however, there are no clear guidelines on specific material properties, cushion testing procedures, and the methodology for evaluating human response effects.

In an extensive program to develop new seat cushion concepts for the AH-64 (Apache) helicopter (Greth, 1994), tests were conducted to compare the vibration attenuation and subjective comfort of the current inventory cushion and prototype cushions (Butler and Alem, 1994). The prototype cushion was designed to accommodate the insertion of either a wedge-shaped foam filled or air filled (inflatable) bladder between foam layers for providing either fixed or adjustable cushion height for thigh support at the forward edge of the seatpan. The subjects were allowed to adjust the air filled thigh support using a bulb-type hand pump prior to testing. Human subjects were exposed to a simulated AH-64 flight profile for one hour. The frequency transfer functions were calculated and averaged from the acceleration signals measured at the seat bottom and at the human/cushion interface in the three translational axes. The averaged functions were integrated in the frequency range of 4 to 8 Hz and 20 to 40 Hz and statistically evaluated for the vertical results. As compared to the current inventory cushion, the prototype cushion was found to significantly attenuate the transmission of vibration to the buttocks in the higher frequency range of 20 to 40 Hz. The data did show that there was a slight increase in the vibration transmission in the lower frequency range for the prototype as compared to the inventory cushion. The subjective comfort assessment showed that, overall, the subjects favored the increased vibration attenuation at the higher frequencies and found the prototypes to be more comfortable as compared to the inventory cushion.

While the significance of vibration in contributing to low back pain during helicopter flight is not well understood, minimizing the transmission of vibration during prolonged operations, particularly in regions of greatest human sensitivity, is expected to play a major role in reducing discomfort. Although the prototype cushion was shown to improve comfort as compared to the current inventory cushion, it provides the opportunity for a more detailed evaluation of human body vibration response. The objective of this study was to conduct a more rigorous analysis of the effects of the current inventory cushion and the deflated and inflated prototype cushions on human vibration response. Both the driving-point impedance and transmissibility techniques were applied. Emphasis was placed on comparing the location and magnitude of human body resonance peaks measured at specific anatomical sites using a rigid seat and the three cushions.

2. METHODS AND MATERIALS

An electrodynamic vibration platform was used to provide the vertical vibration exposures. A human test seat, designed to respond as a rigid mass over the frequency range of concern, was mounted on top of the platform and included a seatback, lapbelt, and double shoulder harness. The transmitted force of the combined seat and human was measured by three load cells located between the seat and vibration platform. Two accelerometers were attached to the seat for measuring the input acceleration magnitude and phase. Vertical accelerations were measured using miniature accelerometers placed on the chest (at the level of the manubrium), at the upper spine region (in the vicinity of the seventh

cervical vertebra on the spinous process), on a bitebar molded with dental acrylic, and at the mid-thigh of the leg. In addition, a ride quality meter, consisting of three orthogonal accelerometers imbedded within a rubber disk, was placed between the subject and seating surface. The three input vibration profiles at the seat included discrete sinusoidal frequencies and two sum-of-sines profiles generated by combining the discrete sinusoidal frequencies. The frequency components used for all three input profiles ranged from 3 to 21 Hz in 1 Hz increments. The seat acceleration level was $0.59 \text{ ms}^2 \text{ rms}$ ($0.06 \text{ g}_{\text{rms}}$). While the frequency content and rms acceleration were identical for the two profiles, the crest factor (CF= 2.9 and 4.2) was varied by altering the phase relations between frequency components. A computer program was used to generate the vibration profiles and for simultaneously collecting all transducer data. Data were collected for two seconds at a sampling rate of 1024 Hz. A Fast Fourier Transform algorithm was used to determine the transducer magnitude and phase difference between the sum of the three load cells and the input velocity calculated from the input acceleration at the seat. Impedance was calculated as the magnitude ratio and phase difference between the transmitted force and input velocity. The impedance of the rigid seat (collected separately) was subtracted from the calculated impedance to obtain the impedance of the subject. The vertical transmissibility magnitudes were calculated as the ratios between the accelerations measured at the anatomical sites and ride quality meter and the input acceleration at the rigid seat. The three magnitude frequency response profiles (sinusoidal and sum-of-sines) were used to compare and evaluate the frequency location and magnitude of the peak or resonance responses. The means and standard deviations were calculated for the resonance frequencies and peak magnitudes extracted from these data. In addition, the mean impedance and transmissibility magnitude frequency responses were calculated from the three profiles. Four seating configurations were evaluated including the rigid seat, the current inventory cushion (Cushion A), the deflated prototype (Cushion B), and the inflated prototype (Cushion C). For the inflated cushion, the bladder pressure was maintained at 551.6 kPa with the subject seated. One-way repeated measures analysis of variance (ANOVA) and the Student-Newman-Keuls multiple comparison test were used for comparing the significance of seating configuration on the frequency and magnitude of the resonance peaks.

Five subjects were selected for testing based on their weight percentiles. They included three 5th percentile (or less) (5%) females weighing between 489 and 569 N, and two 95th percentile (or greater) males weighing between 996 and 1036 N. During the tests, the subjects were loosely restrained by the lapbelt and shoulder harness for safety reasons. Subjects were instructed on the importance of maintaining an upright and consistent seated posture during testing. Female subjects were required to wear upper body athletic support clothing. The one-way ANOVA and Student-Newman-Keuls multiple comparison test were used to compare differences between the females and males.

Both the current inventory and prototype seat pan cushions were fabricated with three layers of foam. In both, the bottom layer consisted of a relatively hard foam contour base. The middle layer was fabricated with an energy-absorbing foam, while the top layer was comprised of polyurethane foam. The energy-absorbing layer was approximately 1.27 cm in the current inventory cushion, and 3.81 cm in the prototypes. The polyurethane layer was approximately 2.54 cm thick in the current inventory cushion, and 1.27 cm in

the prototypes. The current inventory cushion was approximately 38.1 cm in length from front to back, while the prototypes were 45.7 cm. All cushions were covered with a thin wool-like fabric. The prototypes were also covered with sheepskin on the top surface. The inflatable thigh supports were made of heat sealed fabric and contained baffles for maintaining a wedge shape when inflated. The supports were incased in an elastic cover. The thigh supports were inserted in an opening at the front of the cushion between the hard contour and energy-absorbing foam layers. The current inventory cushion weighed approximately 0.795 kg. The prototype cushions weighed approximately 1.65 kg. Further details on the prototypes are provided in Greth, 1994.

In addition to human tests, the three cushions were tested with a rigid mass of 68 kg (667 N) using bags of metal shot. The miniature accelerometers were placed on top of the shot at approximately the center of the cushion (location of the ischial tuberosities for the seated human) and at the front of the cushion (location of the thigh and cushion inflatable bladder). The ride quality meter was placed between the rigid mass and the cushion. Driving-point impedance was calculated as described for the human. Vertical transmissibilities were calculated as the ratios between the accelerations measured on top of the mass and the ride quality meter, and the input acceleration at the rigid seat. The frequency response profiles were used to identify the resonance behaviour of the cushions using a rigid mass representation for the human. Analysis of variance was used to compare the frequency and magnitude of the peak resonance responses between the measurement locations and between cushion configurations.

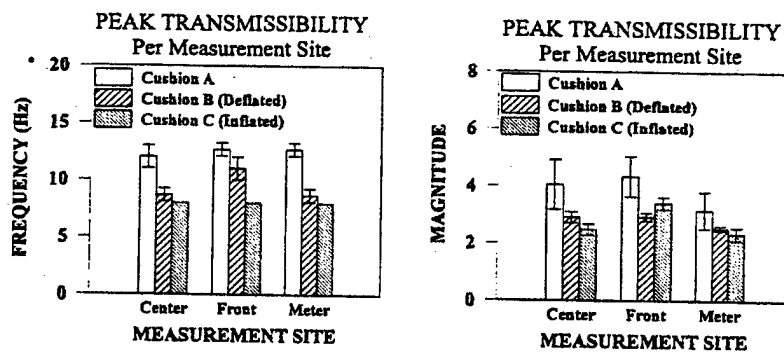


Figure 1 Rigid Mass Tests - Peak Transmissibility per Measurement Site

3. RESULTS

a. Rigid Mass Cushion Tests

All three cushions showed a single dominant resonance peak in the frequency range of 3 to 21 Hz for the rigid mass. Figure 1 illustrates the mean resonance frequencies and peak magnitudes \pm one standard deviation for the transmissibilities observed for the cushions. The resonance frequencies and peak transmissibility magnitudes calculated at the ride quality meter, Figure I Rigid Mass Tests - Peak Transmissibility per Measurement Site center, and front of the cushion were all similar for Cushion A. The two prototypes showed variable results. For Cushion B, the resonance frequency associated with the front measurement site showed a significantly higher frequency as compared to the other sites. The one way repeated measures ANOVA showed that both the center and front peak magnitudes were significantly higher as compared to the ride quality meter although these differences were not dramatic. For Cushion C,

there were no significant differences in the resonance frequencies at the three measurement sites, however, the transmissibility at the front of the cushion was significantly higher as compared to the other sites. These results strongly suggested that the material properties were not evenly distributed in the prototype cushions, and were influenced by cushion inflation. On comparing the three cushions, Cushion A showed a significantly higher resonance frequency for both the impedance (means of 12.67 as compared to 10.67 for Cushion B and 8.0 Hz for Cushion C) and transmissibilities (Figure 1). The only significant differences observed in the resonance frequencies between the two prototypes were the higher frequency produced by Cushion B for the impedance and front transmissibility. In addition, Cushion A also produced higher peak impedances (mean of 21.4 as compared to 11.2 and 10.7 N-s/m $\times 10^3$) and peak transmissibilities as compared to the prototype cushions. While Figure 1 shows that large variability occurred in the transmissibility data for Cushion A, the higher peaks observed for Cushion A were statistically significant at the center and front measurement sites, but not at the ride quality meter. No significant differences were observed in the peak impedance and transmissibilities between the two prototypes (Cushion B and C).

b. Driving-Point Impedance

Figure 2 illustrates the mean impedance magnitude frequency responses for the females and males at each seating configuration. For all seating configurations, both the 5% females and 95% males showed a resonance peak between 4 and 7 Hz, in addition to other resonance peaks located at higher frequencies. Relative to the other peaks, the magnitude of the first peak was much higher for the males than observed for the females. As illustrated in Figure 2, the majority of the rigid seat data showed that the first magnitude peak observed for the females was similar to or lower than the second peak observed between about 8 and 10. The appearance of a higher first resonance frequency for the rigid seat was statistically significant for the males with the mean resonance frequency being about 1 Hz higher, with no significant differences observed between cushions. For the females, the only significant differences in the resonance frequency occurred between the rigid seat and Cushion B (deflated), with the rigid seat mean being higher by less than 1 Hz. For both the females and males, the cushions tended to produce higher magnitude peaks in the first region of resonance located between 4 and 7 Hz as compared to the rigid seat. For the females, both Cushions B and C (deflated and inflated) produced significantly higher peaks as compared to the rigid seat and Cushion A. In contrast, only Cushion A produced a significantly higher magnitude peak as compared to the other seating configurations for the males.

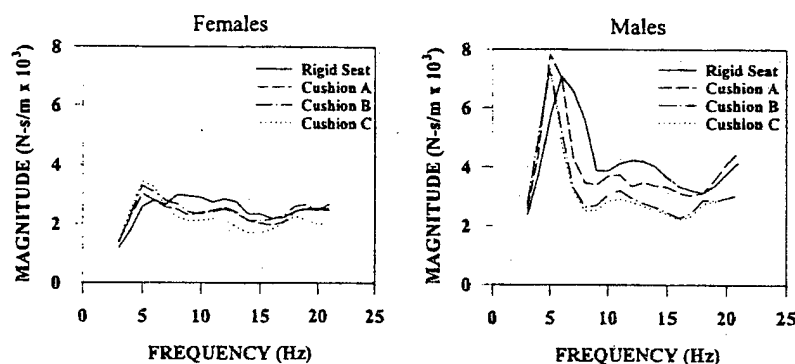


Figure 2 Mean Driving-Point Impedance Frequency Responses

The statistical analysis indicated that the primary impedance resonance frequency observed for the males was significantly higher as compared to the females for all seating configurations. However, the differences in the frequency means were less than 0.5 Hz. As illustrated in Figure 2, the magnitude of the driving-point impedance, particular in the region of the primary peak, was significantly lower in the females as compared to the males. This finding was expected due to the lower body weights of the females. However, when normalized for body weight, the male responses tended to remain higher. The differences were not significant for the rigid seat, but were statistically significant for the cushions.

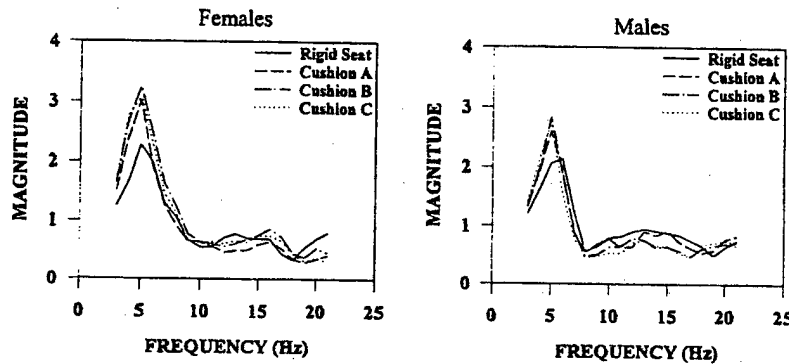


Figure 3 Mean Chest Transmissibility Frequency Responses

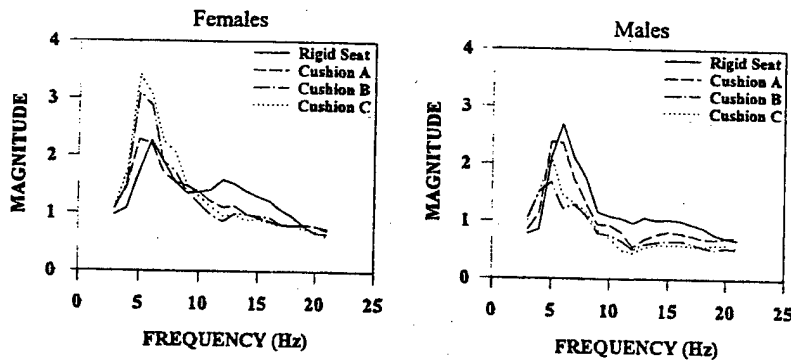


Figure 4 Mean Head Transmissibility Frequency Responses

c. Chest and Head Transmissibility

Figures 3 and 4 illustrate the mean chest transmissibility and mean head transmissibility magnitude frequency responses for the females and males at each seating configuration. The figures show that a prominent chest and head transmissibility peak, located between about 4 and 6 Hz, was produced for both the females and males, coinciding with the first resonance peak observed for the impedance. The females showed similar resonance frequencies for all seating configurations. For the males, the higher resonance frequency occurring for the rigid seat was statistically significant, however, the mean differences were small at about 0.5 Hz. Both the females and males showed statistically significant higher chest transmissibility peaks for all cushions as compared to the rigid seat as illustrated in Figure 3. All cushions showed similar responses. As with impedance, the males showed a significantly higher resonance

frequency for the peak chest transmissibility as compared to the females, however, the differences in the means were less than 0.5 Hz. It was also observed that, in general, higher chest transmissibility peaks occurred in the females as compared to the males. These findings were statistically significant for all cushions, but not for the rigid seat.

Although differences in the means were 1 Hz or less for both the females and males, the higher resonance frequency associated with the peak head transmissibility was statistically significant for the rigid seat. For the males, Cushion A also showed a higher resonance frequency as compared to the prototypes (Cushions B and C). All cushions produced similar resonance frequencies in the females. As illustrated in Figure 4, both prototypes (Cushions B and C) produced higher head transmissibility peaks in the females as compared to the rigid seat and Cushion A with the results being statistically significant. In contrast, the prototype cushions (Cushions B and C) produced statistically significant lower peak head transmissibilities in the males as compared to the rigid seat and Cushion A. Cushion C did produce a significantly higher peak as compared to Cushion B. The higher head transmissibility peaks observed for the females as compared to the males using the prototype cushions were statistically significant. The males, however, did show a significantly higher head transmissibility peak for the rigid seat as compared to the females, while no differences were observed for Cushion A. There were no significant differences in the resonance frequencies associated with the peak head transmissibility between the females and males relative to the seating configuration.

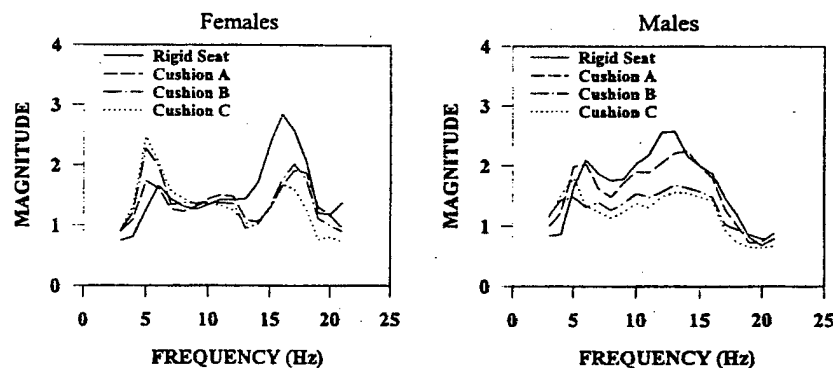


Figure 5 Mean Spine (C_7) Transmissibility Frequency Responses

d. Spine (C_7) Transmissibility

Figure 5 illustrates the mean spine transmissibility magnitude frequency responses for the females and males at each seating configuration. While multiple regions of resonance were evidenced in the profiles, the majority of subjects showed two dominant regions of resonance in the spine transmissibility for the seating configurations used in this study. The first region was observed between about 4 and 6 Hz, again, coinciding with the location of the peak impedance, and peak chest and head transmissibilities. The second region was observed between 16 and 18 Hz for the females, and between about 10 and 13 Hz for the males. The first resonance frequency for both the females and males was higher for the rigid seat (by a maximum of about 1 Hz between means). For the males, both the rigid seat and Cushion A produced higher resonance frequencies. All of these results were statistically significant. For the

females, all cushions showed higher peak magnitudes in the first resonance region as compared to the rigid seat, the results being statistically significant. Cushion C also produced significantly higher peaks as compared to Cushion B. Both prototypes showed dramatically higher peaks as compared to Cushion A as illustrated in Figure 5. In contrast, the males showed that both prototypes produced significantly lower transmissibility peaks as compared to the rigid seat and Cushion A. The peak transmissibilities were shown to be significantly higher with the use of Cushion C as compared to Cushion B, as observed for the females. These results were similar to the findings observed for the head transmissibility with the prototype cushions showing significantly higher magnitude peaks in the females as compared to the males. The males did show significantly higher magnitude peaks for both the rigid seat and Cushion A as compared to the females. Again, no significant differences were found in the location of the associated resonance frequencies between the females and males relative to the seating configuration.

The second region of resonance produced the highest peak in the spine transmissibility for the majority of the subjects as illustrated in Figure 5. Cushions A and B showed higher resonance frequencies as compared to rigid seat and Cushion C for the females. While these results were statistically significant, the differences in the means were 1 Hz or less. No significant differences were observed in the resonance frequencies between seating configurations for the males, with large variations being observed in the data. For the females, the rigid seat showed higher transmissibility peaks in the second region of resonance as compared to the cushion configurations, with the results being statistically significant, even though large variations were observed in the data for the rigid seat. All seating configurations showed large variations in the peak transmissibility magnitude for the males, however, the rigid seat did show a significantly higher value as compared to the two prototypes (Cushions B and C). No significant differences were observed in the peak magnitudes between the cushions for either the females or males. Figure 5 shows that all cushions reduced or attenuated the peak response at the higher frequencies. Even though the differences in the location of the resonance frequencies were statistically significant between the females and males, both showed similar magnitude peaks for the respective seating configuration.

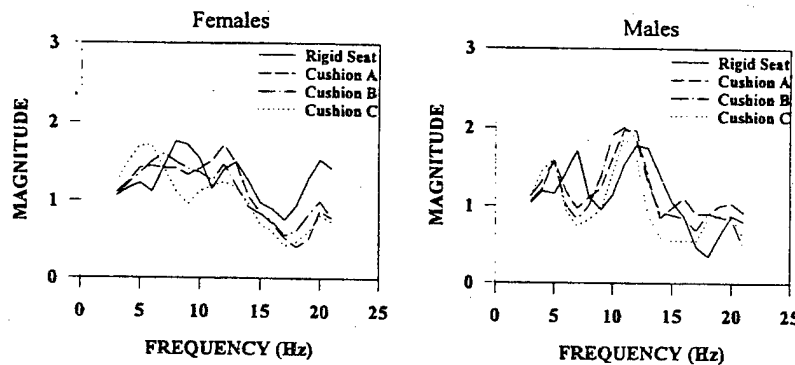


Figure 6 Mean Leg Transmissibility Frequency Responses

e. Leg Transmissibility

Figure 6 illustrates the mean leg transmissibility magnitude frequency responses for the females and males at each seating configuration. Multiple transmissibility peaks were observed at the thigh, however, two regions of

resonance were more prominent and consistently observed. The first region occurred between 5 and 8 Hz for the females, and between 4 and 7 for the males. The second peak occurred between about 11 and 14 Hz for both females and males. For the first region of resonance, the rigid seat produced statistically significant higher resonance frequencies, with the mean differences being as great as 2-3 Hz for both the females and males as compared to the cushions. Large variations were observed in the resonance frequencies for the females with Cushions A and B producing a higher resonance frequency as compared to Cushion C.

These results were statistically significant with the differences in the means being greater than 1 Hz. Interestingly, there were no significant differences in the magnitude peaks associated with the first resonance frequency between the seating configurations for either the females or the males. Except for Cushion C, the females showed significantly higher resonance frequencies as compared to the males, the largest differences occurring for the deflated prototype (Cushion B) with a mean difference of 2 Hz. The peak magnitudes were similar between the females and males for all seating configurations.

For the females, the resonance frequency associated with the second transmissibility peak showed relatively large variations, as observed for the first peak. As a results, there were no significant differences observed among the seating configurations. For the males, the rigid seat showed a statistically significant higher resonance frequency for the second peak, however the differences between the means were about 1 Hz, less than the differences observed for the females. Although Cushion C showed the lowest transmissibility at the second resonance peak for the females, the results were not statistically significant. All magnitude peaks were similar in the second region of resonance for the males. Even with the large variability, Cushion B produced significantly higher resonance frequencies in the females (mean difference of 2 Hz) while the peak magnitudes were similar between the females and males.

f. Ride Quality Meter

The single peak observed in the transmissibility frequency responses at the interface between the subject and cushion occurred between about 4 - 5 Hz for both females and males. The females showed insignificant differences in the resonance frequencies between all seat configurations. For the males, the resonance frequency was higher with the use of Cushion A as compared to Cushion C (inflated) (mean of 4.67 Hz compared to 4.0 Hz) and statistically significant. Even though the higher peak magnitudes produced by the prototypes as compared to Cushion A for the females were statistically significant, the differences were quite small means of 1.23 and 1.24 as compared to 1.10). For The males, Cushion C produced a statistically significant higher peak (mean of 1.3) as compared to Cushion B (mean of 1.24), and both were significantly higher than Cushion A (mean of 1.15). The results for the females and males were similar at each seating configuration. The data collected at the interface did not reflect the significance of the results observed at other anatomical sites.

4. DISCUSSION AND CONCLUSIONS

The results of the rigid mass tests indicated that there were significant differences in the stiffness and damping properties between the cushions, particularly between the current inventor and two prototype cushions, for the

test conditions used in this study. As reflected by the location of the resonance frequencies, it appeared that, in general the prototype cushions were less stiff with greater vibration attenuation capability as compared to the current inventory cushion. Inflating the front region of the prototype (Cushion C) did appear to decrease the otherwise higher stiffness observed at the front of the cushion when deflated (Cushion B). In addition, inflation to 551.6 kPa appeared to produce a more even distribution of response characteristics in the prototype for the loading conditions used in this study. The higher peak transmissibility observed at the front of the inflated cushion suggested that there may be some decrease in the vibration attenuation characteristics at the front relative to the center of the cushion.

All three cushions increased the magnitudes of the peak impedance and chest transmissibility for both the females and males in the region of greatest human sensitivity (4 - 8 Hz). In contrast, the cushions attenuated the resonance responses observed at higher frequencies as evidenced in the second spine transmissibility peak for both the females and males. The reduced response was also noted in the impedance frequency response profiles at higher frequencies. Specifically, it is expected that differences in cushion response properties, as particularly observed between the current inventory cushion and two prototype cushions, would influence the transmission and attenuation of vibration in the human body as was found in previous studies using different cushions (Smith, 1994a and Smith, 1996). However, findings observed in both the present and previous study (Smith, 1996) emphasize that differences in the distribution of mass, stiffness, and damping properties among the major anatomical regions may be an important consideration in designing seats and cushions for minimizing vibration transmission. The significantly lower resonance frequency observed for the males in the second spine resonance region specifically showed that differences in the mass, stiffness, and damping properties of the spine exist between the larger males and smaller females. These differences may be the major contributing factor to the contrasting effects observed at the head and spine at low frequencies with the use of the prototype cushions. The upper torso and spine have been successfully modelled as mechanically coupled structures in which the motion of one system is influenced by the motion of the other (Smith, 1994b). The coincidence of the spinal peak at 4 - 6 Hz, in addition to the resonance behaviour located above 12 Hz, can be considered the result of this influence due to the major contribution of the upper torso to human resonance in the frequency range of 4 to 8 Hz (Guignard and Irving, 1960). The transmission of vibration to the head depends on this coupling behaviour. In this study, the similarity between the responses of the head and spine at the lower frequencies strongly suggested that the spinal column had a significant influence on head motion at the lower frequencies.

Inflating the bladder to 551.6 kPa did not have a dramatic effect on human vibration response. The differences observed in the rigid mass tests relative to the location of the bladder, suggested that the inflated bladder would specifically affect leg transmissibility, however, all cushions produced similar transmissibility peaks at the thigh for the inflation pressure used in this study. With the inflated prototype, however, the peak transmissibilities observed between 4 and 6 Hz were statistically higher at the head (males) and spine (females and males) as compared to the deflated prototype. Although not dramatic, these results suggested that the greatest influence of the bladder may be on vibration transmission in the spine. To further study the influence of the

inflatable thigh support, tests should be conducted using variable bladder pressures. Since posture can affect the transmission of vibration in the human body, spinal posture should be evaluated as a function of bladder inflation.

In general, the prototype cushion concept tested in this laboratory tended to reduce the transmission of vibration to specific anatomical sites in the larger males as compared to the current inventory cushion. However, the contrasting results observed for the females strongly indicated that improvements to helicopter seat cushion design concepts should consider the dependence of vibration transmission characteristics on the sex and size of the occupant.

5. ACKNOWLEDGMENTS

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